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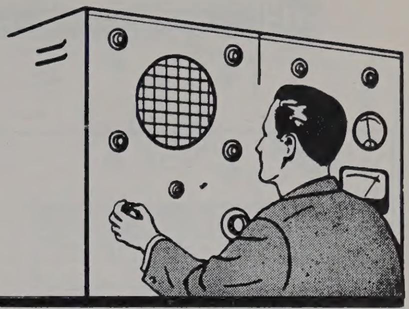

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The Aerovox Research Worker is edited and published by the Aerovox Corporation to bring to the Radio Experimenter and Engineer, authoritative, first hand information on capacitors and resistors for electrical and electronic application.

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Semiconductor Devices as Nonlinear Resistors

By the Engineering Department, Aerovox Corporation

Modern sophisticated electron design often calls for a nonohmic resistance element; i. e., one in which R varies nonlinearly with current or voltage (and sometimes which may vary approximately linearly but is dc-sensitive). This requirement is not recent in origin, however, as is attested by the article "Nonlinear Resistors" in the October-November 1953 issue of the *Research Worker*.

That article was devoted only to the nonohmic resistance of thyrite, thermistors, tungsten-filament lamps, forward-biased germanium diodes, and miniature fuses. But during the ensuing decade, other components have become available, which extend the usefulness of nonlinear resistance.

Other components in which nonlinear resistance is available as a supplementary effect, and which merit present discussion, include silicon diodes and rectifiers, zener diodes, transistors, and tunnel diodes. The peculiar resistance characteristic of these components opens new vistas of application in control, computation, instrumentation, and communications. The performance of these components is discussed separately below.

SILICON DIODE

Forward-biased germanium small-signal diodes have long been used as nonlinear resistors to provide an average resistance variation of 100:1 (resistance decreases from 10,000 ohms to 100 ohms as the diode voltage drop is increased from 0.1 v to 1 v). Forward-biased small-signal silicon diodes provide similar nonlinear resistance change, with the added advantage of improved temperature characteristics.

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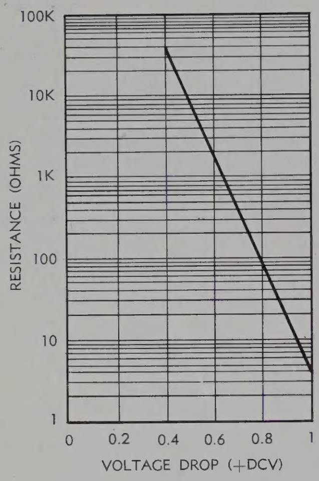

FIGURE 1

RESISTANCE CHARACTERISTIC OF PLANAR PASSIVATED EPITAXIAL SILICON DIODE

Figure 1 shows the resistance-vs-dc voltage characteristic of a forward-biased (i. e., anode positive, cathode negative) planar epitaxial passivated silicon diode (General Electric Type 1N3606) at 25°C. Note that the resistance decreases from 40K at 0.4 vdc to 4 ohms at 1 vdc, a resistance change of 1000:1 for a voltage change of 2.5:1. Corresponding current levels are 0.01 ma at 40,000 ohms, and 25 ma at 4 ohms. At +150°C, the resistance change, for the same voltage change, becomes 266 ohms to 3.3 ohms, and at −55°C, it becomes 4 megohms to 33 ohms.

SILICON RECTIFIERS

When a high value of current and/or voltage must be used in a nonlinear circuit, a silicon rectifier having suitable continuous dc ratings must be substituted for the small-signal diode.

Rectifiers (sometimes called *power diodes*) are supplied in a wide variety of current and voltage ratings — from less than 100 v to several kv, and from a few milliamperes to several hundred amperes. Correspondingly varied resistance values (both from a standpoint of absolute levels and range of variation) are provided by these rectifiers. Figure 3, for example, shows the resistance characteristic of an 850-ma rectifier (RCA Type CR101). Here, the resistance decreases from 1.8 ohm to 0.23 ohm (a resistance change of 7.84:1) as the forward d-c voltage is increased from 1.8v to 3.4v. (This corresponds to a current variation from 1 A to 15A. A rectifier may be selected to operate at the current and/or voltage available for the application, and the obtainable resistance range then may be determined from calculations of static d-c E/I values, the slope of the resulting curve resembling that given in Figure 2.

Like the small-signal silicon diode, the silicon rectifier has improved temperature ratings, compared with those of its germanium counterpart.

ZENER DIODE

Operation of the zener diode is characterized by its sharp reverse breakdown (rapid increase of current at a discrete reverse voltage). This peculiarity, which has been much exploited in voltage regulation, gives rise to a distinctive nonlinear resistance feature. The zener diode is reverse-biased; i. e., anode negative and cathode positive.

Figure 3 shows the resistance characteristic of a reverse-biased 3.9-volt zener diode (International Rectifier Type 1N1518). Here, the resistance decreases from 140K to 11 ohms as the voltage drop is increased from 0.6 v to 3.9 v (a resistance change of 12,700:1 for a voltage change of 6.5:1). The corresponding current increases from 4 microamperes to 250 milliamperes.

Zener diodes are available in a wide variety of current, voltage, and power ratings. As is true with small-signal diodes and rectifiers, a unit may be chosen to withstand current and/or voltage available in the circuit. The obtainable resistance range then may be determined from static d-c E/I calculations, the slope of the resulting curve resembling that given in Figure 3.

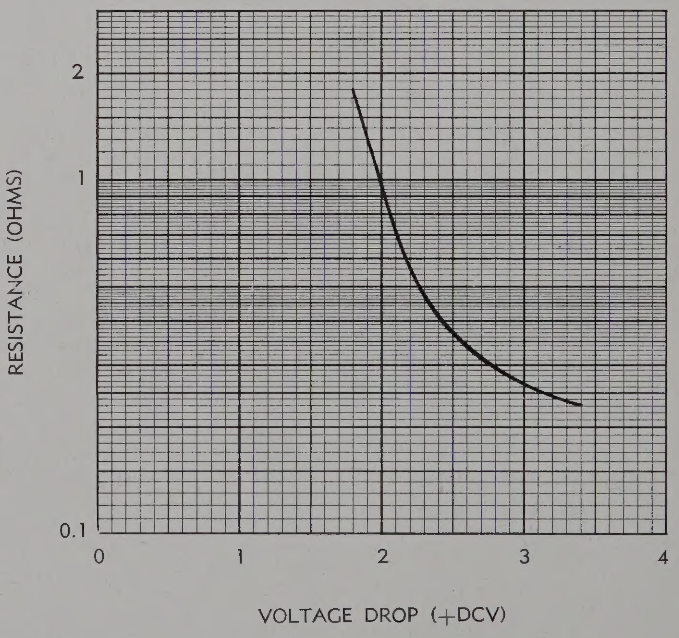

FIGURE 2. RESISTANCE CHARACTERISTIC OF SILICON POWER RECTIFIER (RCA CR101)

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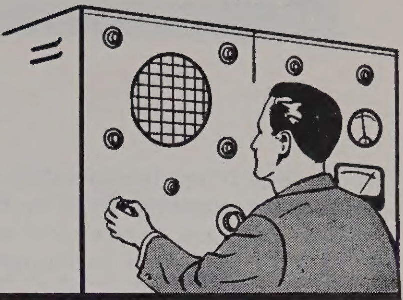

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Accuracy of Capacitance Measurements

How closely may capacitance be measured with a given type of instrument? Will a capacitance meter suffice for a particular measurement; and if not, will a low-priced, medium-priced, or high-priced bridge be required? Or is some other instrument suitable? These are questions which arise naturally in the mind of a serious worker with capacitors. And they find no satisfactory answer in the commonplace that "A bridge is better than a meter."

A number of capacitance-measuring instruments and setups are in regular use. And, in fact, their number is large enough to confuse the nonspecialist. Some have been chosen on the basis of best suitability, while others owe their adoption to availability, low cost, familiarity, or plain accident. The new user must select the correct instrument for his purposes and he has few guideposts. It is not a matter of rationality of instrumentation — i.e., avoidance of overinstrumentation and underinstrumentation (ordinarily, one never expects to find a radio and television service shop equipped with a 2000 capacitance bridge, nor an engineering research laboratory with a kit-type capacitance meter) — but one of suitability. What instrument should I have?

Where capacitance measurement is the sole requirement and a number of instruments provide the same capacitance ranges and test voltages, accuracy sufficient for the purpose seems to be the best criterion for selecting the instrument. It is not unusual that capacitance measurement accuracy should differ between the various measurement systems, since they employ different numbers of components, each of which is subject to shift in value, and different controls and adjustments. Furthermore, they employ different circuits and methods of readout. This article compares the accuracy of common capacitance measuring instruments, based upon a study of performance data, instrument manufacturer's specifications, and current literature.

Measuring Instruments and Accuracies

CAPACITANCE METERS. These are the simplest instruments for measuring capacitance, since, like nonelectronic voltmeters or current meters, they require no manipulation. They are most useful in test operations, such as troubleshooting, where a direct indication of capacitance is desired at the greatest possible speed. There are four principal varieties: *reactance meter*, *ratio meter*, *beat-frequency meter*, and *multi-vibrator meter*.

The simple, service-type *reactance meter* is essentially an a-c milliammeter connected in series with a known a-c voltage and the unknown capacitor. Ideally, current flowing through the circuit is proportional to voltage and reactance, and assuming constant voltage and frequency, the meter scale accordingly may be graduated directly in microfarads. Several capacitance ranges may be provided. Simple reactance meters, such as those employed in electronic ser-

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vicing and often incorporated in multimeters, operate from a 60-cycle voltage.

This is the least accurate type of capacitance meter, ±5% to ±15% of indicated value being common. A part of its inaccuracy is due to the fact that this instrument circuit responds not simply to the reactance of the test capacitor, but actually to its impedance. If the resistive component of this impedance is significant in magnitude, therefore, the meter scale (which has been calibrated on the basis of pure capacitance and reactance only) may be appreciably in error. It is possible, for example, for the percent error to be equal numerically to the power factor of a capacitor under test. Other important causes of error are difficulty in holding the test voltage and sometimes the test frequency constant, and inaccuracies in the rectifier-type indicating meter.

A laboratory-type capacitance meter of the reactance type has appeared relatively recently, in which the shortcomings of the simple service-type instrument have been eliminated. Improved accuracy (±2% to ±5% of indicated capacitance) has been obtained by use of a frequency-stabilized and voltage-stabilized internal 1000-c/s test signal source, very-low resistances across which the capacitor current develops the indicator voltage, and an accurate vacuum-tube millivoltmeter (rather than a rectifier-type milliammeter or microammeter) as the indicator.

The *ratio meter* is an electrodynamometer-type instrument which reads directly in microfarads. Its operation is almost free from the effects of test voltage, test frequency, and capacitor power factor (however, the phase angle of the capacitor must not exceed 3 degrees). Accuracy is 1% of full scale below 0.3 ufd, and 0.333% of full scale at 0.3 ufd and higher. This type of instrument is supplied for use at specified frequencies of 50, 60, or 500 c/s and specified a-c line voltages of 100-130 v and 200-250 v.

Like the laboratory-type reactance meter, the *beat-frequency* meter is a refined instrument. It contains two highly stable oscillators, one fixed in frequency and one variable, which are set initially to zero beat with each other. The unknown capacitor then is connected in parallel with the tank of the variable oscillator, which it accordingly detunes. This causes a beat note to be generated at a frequency equal to the difference between the two oscillator frequencies, and this beat-note signal actuates a direct-reading electronic audio frequency meter. The scale of the latter is graduated directly in picofarads instead of cycles per second. This direct-reading instrument has an accuracy of 3% of full scale.

In the *multivibrator-type meter*, a constant-amplitude, constant-frequency, square wave voltage, generated by a free-running multivibrator, is applied to a rectifier-type a-c meter in series with the unknown capacitor. Under conditions of constant amplitude and frequency, the deflection of the meter is proportional to the capacitance, and the meter consequently may be graduated directly in picofarads. Capacitance ranges are changed by switching the frequency of the multivibrator in discrete steps. Accuracy of this instrument is of the order of ±5% of indicated capacitance.

RESONANT CIRCUIT. An unknown capacitance (C) may be connected in parallel with an accurately known inductance (L) to form a test tank circuit, and the resonant frequency (f) of this combination determined by means of a signal generator loosely coupled to the tank. At resonance, the voltage across the capacitor is maximum and may be indicated by a high-impedance a-c vacuum tube voltmeter connected in parallel with C.

After the resonant frequency has been determined, the unknown capacitance may be calculated from the known tank constants: $C=1/(4\pi^2f^2L)$. This method of measurement makes no allowance for distributed capacitance of the inductor or for stray circuit capacitance, so that the calculated capacitance may be significantly inaccurate because of these parameters. Also, the frequency must be known closely, otherwise the measurement error may exceed the specified tolerance of the capacitor under test.

The resonant-circuit method is often used with a temporary bench setup of signal generator, inductor, unknown capacitor, and vacuum tube voltmeter. If the wiring is rigid, connections short, and test area free of electrical interference, accuracy of ±5% to ±20% may be expected, depending upon the precision and stability of the signal generator and freedom from strays. This may be improved by subtracting the distributed capacitance of the inductor from the calculated capacitance value.

Some self-contained capacitance checkers of the resonant-circuit type dispense with the calculation by graduating the signal generator dial directly in picofarads and microfarads. (This was done in the Aerovox L-C Checker.)

Capacitance sometimes is measured by this method, using a Q meter. The latter provides the tunable signal generator, accurate inductor, and vacuum tube voltmeter in a more efficient circuit.

BRIDGES. The unreserved opinion occasionally is expressed that a capacitance bridge necessarily is more accurate than any other type of capacitance-measuring instrument. The assumption ostensibly rests upon the fact that the bridge compares the unknown with a standard capacitor. The statement needs qualification, however, for much depends upon the type of bridge and quality of its components. For example, a high-priced laboratory-type bridge employs highly stable standard capacitors rated at 0.05% or better accuracy, and a precision potentiometer as the adjustable element, whereas a low-cost service-type bridge intended for radio and television troubleshooting usually contains specially selected commercial capacitors (culled for ±1% to ±2% accuracy) and a volume control-type potentiometer.

The bridge circuit is important. While several types may be used for capacitance measurement, those in which a frequency term appears in the null equation (e.g., Wien and resonance bridge circuits) generally are avoided because of the need for frequency stability in excess of desired measurement accuracy. Even when the frequency is of no consequence, other factors which may introduce error include shifts in potentiometer, ratio resistors, standard capacitor, and circuit capacitances. The Schering and comparison-bridge circuits are most often used.

Capacitance Bridge. Accuracy of the laboratory-type bridge for direct capacitance measurements lies between 0.01% and ±0.25% of indicated capacitance, depending upon model and manufacture. At the other extreme is the service-type bridge, the accuracy of which is not often specified but may be found to be of the order of ±5% in factory-built models and somewhat poorer in some kit-assembled instruments. Most of the service-type bridges combine capacitance and resistance measurement.

Impedance Bridge. This instrument combines capacitance, inductance, and resistance measurements in several ranges. Its accuracy lies between ±0.1% and ±2% of indicated capacitance in factory-built instruments, depending upon model and manufacture. Impedance bridges assembled from kits may show an accuracy of ±2% to ±10%, depending upon care of assembly and calibration.

SUBSTITUTION CIRCUITS. Substitution-type measurements compensate automatically for stray and distributed capacitance, thereby eliminating error due to that source (see *Aerovox Research Worker*, Oct.-Nov.-Dec., 1962). The nucleus of the substitution circuit is a precision, direct-reading variable capacitor. The circuit, which may be either a bridge, twin-T network, or resonant tank, is adjusted first with the variable capacitor set to its maximum capacitance (C_1). At this setting, the bridge or T-network is nulled, or the input to the tank is adjusted to the resonant frequency, and the unknown capacitor is not in the circuit. The unknown then is connected and the circuit readjusted by reducing the variable capacitance to a value C^2 until null (or resonance) is restored. The unknown capacitance $C_X = C_1 - C_2$. Thus, the unknown capacitance is equal to the capacitance removed from the circuit to compensate for the "detuning" action of the unknown capacitor.

Accuracy of the substitution method depends upon the accuracy of the variable capacitor. This generally is less than ±0.05%, depending upon model and manufacture. Measurements with a variable capacitor of the air-tuned type usually are limited to a maximum of 1150 pf, the maximum capacitance of most precision air variable capacitors. A precision decade capacitor may, of course, be used in lieu of the air variable, with an accuracy of the order of ±0.25%.

Substitution-type measurements of capacitance often are made with a Q meter, which supplies the signal generator and direct-reading variable capacitor, together with very-high-impedance a-c vacuum tube voltmeter. Accuracy with this instrument is of the order of ±1 pf below a dial setting of 100 pf, and ±1% above 100 pf (the common dial maximum is 450 pf).

Required Accuracy

What accuracy is actually required? This depends upon the capacitor application. Obviously, wider tolerances are allowable in some applications than in others and this will dictate the required accuracy of measurement. For example, capacitance must be as close as possible to specified value when a capacitor is to be used in an RC or LC tuned circuit, wave filter, or timing circuit, but it may vary ±10% to ±20% (and often more) of nominal value in some bypass and coupling applications where critical time constants are not involved. Filter capacitors in power supplies also may have a wide tolerance in most instances.

In general, capacitance must be known most closely in those applications in which the capacitance directly affects a frequency, time, or phase value (tuned circuits, delay devices, timers, multivibrators, wave filters, phase shifters, critical coupling, critical bypassing, sync circuits) and less closely (but to a degree better than the specified tolerance) in those circuits which do not involve those sensitive terms (power supply filters, energy storage, noncritical bypassing, non critical coupling, d-c blocking, interference elimination). The precision of measurement needed for the first requirement is, of course, not needed for the second requirement. A useful rule of thumb is to determine the maximum error which can be tolerated in the application and then to select the instrument or measuring circuit which affords an accuracy of one-half that figure.

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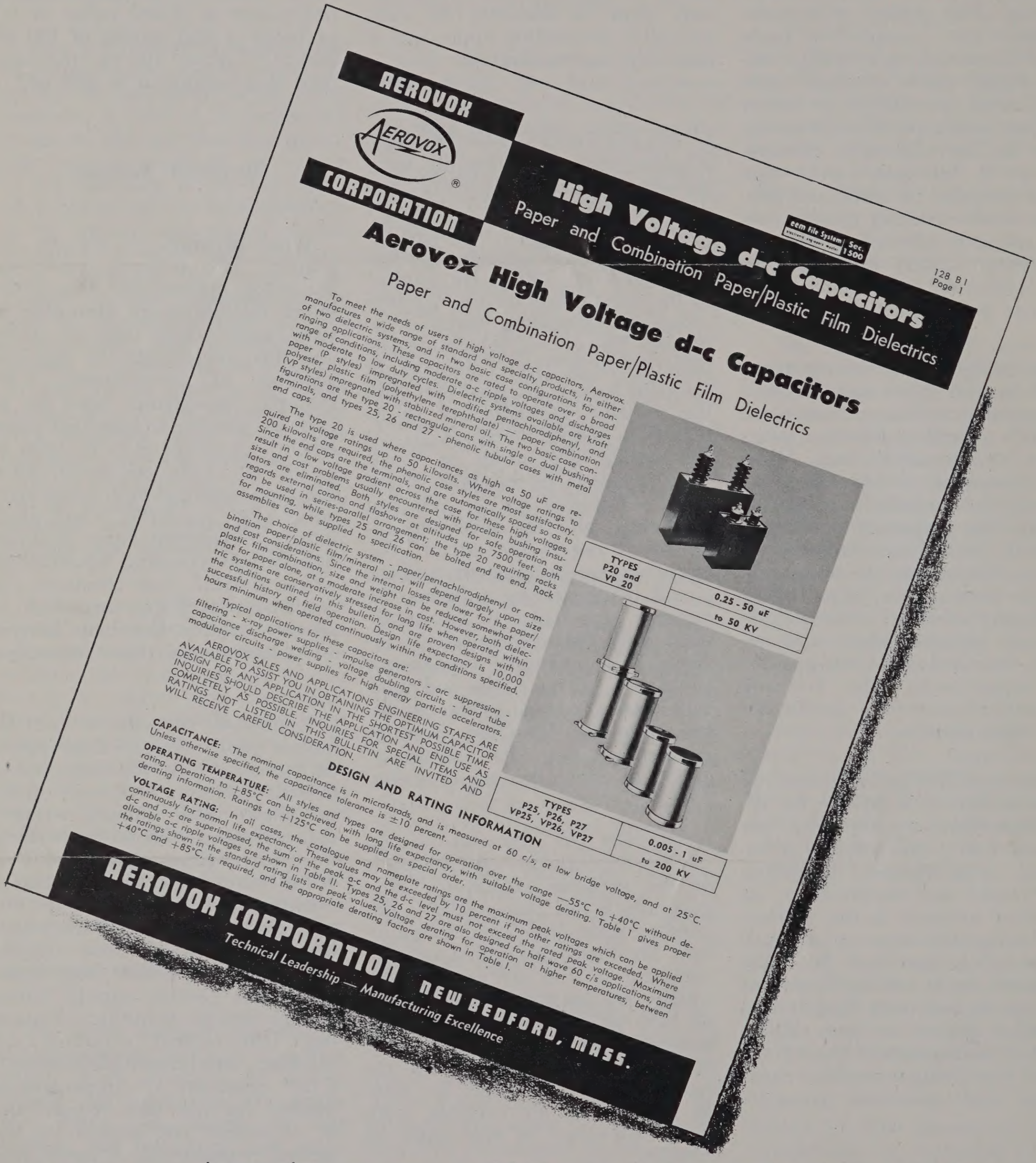
HIGH VOLTAGE DC CAPACITORS



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High Voltage d-c Capacitors
Paper and Combination Paper/Plastic Film Dielectrics

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Aerovox High Voltage d-c Capacitors
Paper and Combination Paper/Plastic Film Dielectrics

To meet the needs of users of high voltage d-c capacitors, Aerovox manufactures a wide range of standard and specialty products, in either of two dielectric systems, and in two basic case configurations for non-ringing applications. These capacitors are rated to operate over a broad range of conditions, including moderate a-c ripple voltages and discharges with moderate to low duty cycles. Dielectric systems available are kraft paper (P styles) impregnated with modified pentachlorodiphenyl, and polyester plastic film (polyethylene terephthalate) — paper combination (VP styles) impregnated with stabilized mineral oil. The two basic case configurations are the type 20 - rectangular cans with single or dual bushing terminals, and types 25, 26 and 27 - phenolic tubular cases with metal end caps.

The type 20 is used where capacitances as high as 50 uF are required at voltage ratings up to 50 kilovolts. Where voltage ratings to 200 kilovolts are required, the phenolic case styles are most satisfactory. Since the end caps are the terminals, and are automatically spaced so as to result in a low voltage gradient across the case for these high voltages, size and cost problems usually encountered with porcelain bushing insulators are eliminated. Both styles are designed for safe operation as regards external corona and flashover at altitudes up to 7500 feet. Both can be used in series-parallel arrangement; the type 20 requiring racks for mounting, while types 25 and 26 can be bolted end to end. Rack assemblies can be supplied to specification.

The choice of dielectric system - paper/pentachlorodiphenyl or combination paper/plastic film/mineral oil - will depend largely upon size and cost considerations. Since the internal losses are lower for the paper/plastic film combination, size and weight can be reduced somewhat over that for paper alone, at a moderate increase in cost. However, both dielectric systems are conservatively stressed for long life when operated within the conditions outlined in this bulletin, and are proven designs with a successful history of field operation. Design life expectancy is 10,000 hours minimum when operated continuously within the conditions specified.

Typical applications for these capacitors are: filtering - x-ray power supplies - impulse generators - arc suppression - capacitance discharge welding - voltage doubling circuits - hard tube modulator circuits - power supplies for high energy particle accelerators.

AEROVOX SALES AND APPLICATIONS ENGINEERING STAFFS ARE AVAILABLE TO ASSIST YOU IN OBTAINING THE OPTIMUM CAPACITOR DESIGN FOR ANY APPLICATION IN THE SHORTEST POSSIBLE TIME. INQUIRIES SHOULD DESCRIBE THE APPLICATION AND END USE AS COMPLETELY AS POSSIBLE. INQUIRIES FOR SPECIAL ITEMS AND RATINGS NOT LISTED IN THIS BULLETIN ARE INVITED AND WILL RECEIVE CAREFUL CONSIDERATION.

TYPES
P20 and
VP 20

0.25 - 50 uF
to 50 KV

TYPES
P25, P26, P27
VP25, VP26, VP27

0.005 - 1 uF
to 200 KV

DESIGN AND RATING INFORMATION

CAPACITANCE: The nominal capacitance is in microfarads, and is measured at 60 c/s, at low bridge voltage, and at 25°C. Unless otherwise specified, the capacitance tolerance is ±10 percent.

OPERATING TEMPERATURE: All styles and types are designed for operation over the range —55°C to +40°C without derating. Operation to +85°C can be achieved, with long life expectancy, with suitable voltage derating. Table 1 gives proper derating information. Ratings to +125°C can be supplied on special order.

VOLTAGE RATING: In all cases, the catalogue and nameplate ratings are the maximum peak voltages which can be applied continuously for normal life expectancy. These values may be exceeded by 10 percent if no other ratings are exceeded. Where d-c and a-c are superimposed, the sum of the peak a-c and the d-c level must not exceed the rated peak voltage. Maximum allowable a-c ripple voltages are shown in Table II. Types 25, 26 and 27 are also designed for half wave 60 c/s applications, and the ratings shown in the standard rating lists are peak values. Voltage derating for operation at higher temperatures, between +40°C and +85°C, is required, and the appropriate derating factors are shown in Table I.

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Latest data are now available on paper and combination paper/plastic film dielectrics. Up to date information on Aerovox types P20 and VP20 from 0.25 to 50 uf — to 50 KV and types P25, P26, P27, VP25, VP26, and VP27 from 0.005 — 1 uf to 200 KV.

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Figure 6 shows the circuit for a field effect transistor. Here, R is a 50,000-ohm ½-watt resistor, B a 1½-volt bias battery, and X the field effect transistor (Amelco Type FE200). The resistance available at terminals A and B (with A positive) increases from 10K to 41K as the applied voltage is increased from 5 v to 45 v (corresponding to a current change from 0.5 ma to 1.1 ma).

Selection of Transistor Resistance Range. Changing the emitter-base input bias will change the resistance of the transistor at any discrete value of collector voltage. Thus, the resistance range of any transistor, together with its absolute resistance limits, may be selected simply by changing the value of fixed bias — current bias in conventional small-signal and power types; voltage bias in the field effect type.

TUNNEL DIODE

The forward-biased tunnel diode provides not only nonlinear resistance, but also negative resistance over a portion of its E/I characteristic. Figure 7 shows how this resistance varies with low values of forward d-c voltage drop in a General Electric Type 1N2940 tunnel diode.

The diode resistance is positive and stable between its 10-mv and 55-mv values, negative and unstable from 55 mv to 350 mv, and positive and stable again from 350 mv to 400 mv and beyond. The current peak (1 ma) occurs at 55 mv, and the current valley (0.1 ma) at 350 mv, for the particular diode tested by the editors.

WHERE USED

Some of the automatic actions provided in a simple manner by nonlinear resistors include voltage regulation, frequency multiplication (harmonic generation), curve shaping, curve correction, amplitude stabilization, signal compression, signal expansion, modulation, bias control, signal damping, instrument protection, and transient suppression. The semiconductor devices discussed in this article have extended the range of usefulness of nonlinearity and are valuable additions to the stock of early nonlinear resistors.

Equipment in which nonlinear resistor action may be exploited include test instruments, control devices, communications apparatus, electromedical gear, and domestic and industrial electrical and electronic machinery.

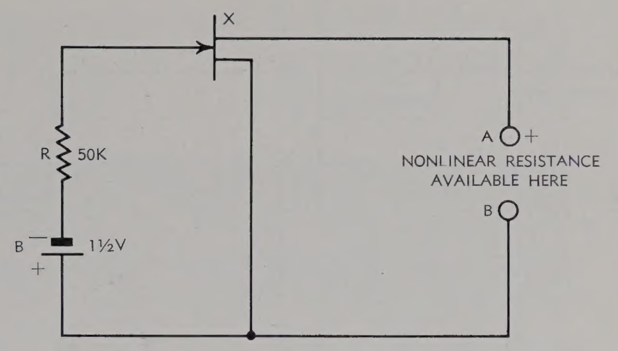


FIGURE 6. FIELD EFFECT TRANSISTOR AS NONLINEAR RESISTOR

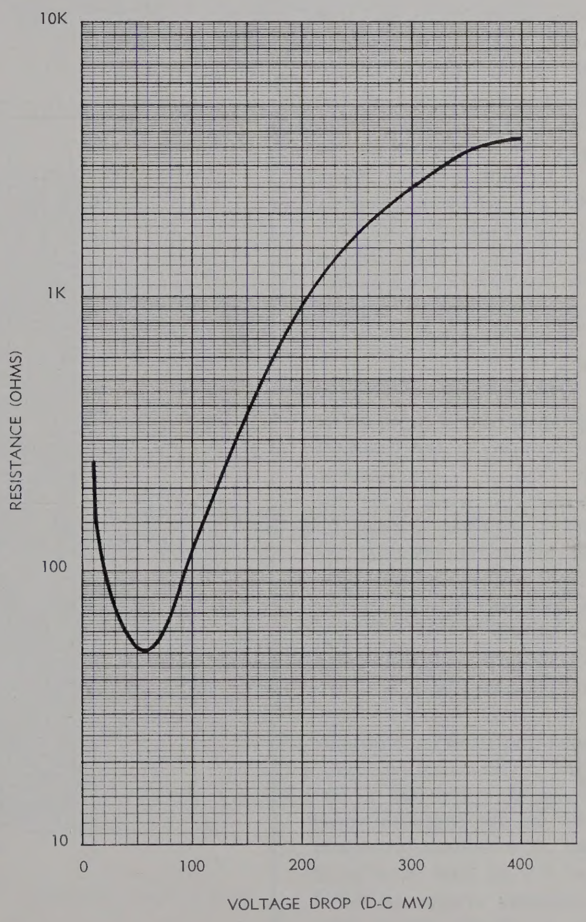
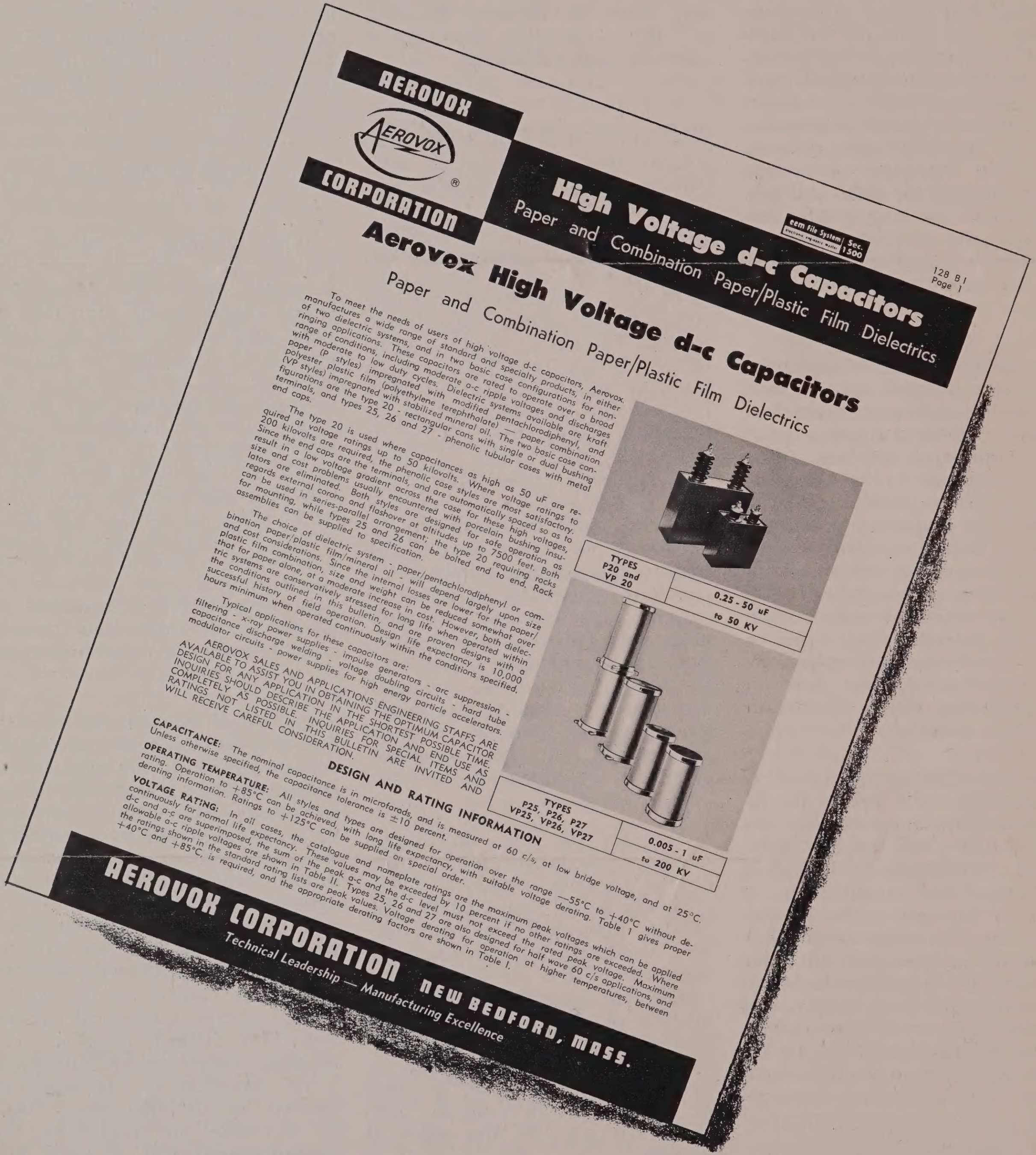


FIGURE 7. RESISTANCE CHARACTERISTIC OF TUNNEL DIODE

HIGH VOLTAGE DC CAPACITORS



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High Voltage d-c Capacitors
Paper and Combination Paper/Plastic Film Dielectrics

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Aerovox High Voltage d-c Capacitors

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TYPES P20 and VP 20 — 0.25 - 50 uF to 50 KV

TYPES P25, P26, P27 VP25, VP26, VP27 — 0.005 - 1 uF to 200 KV

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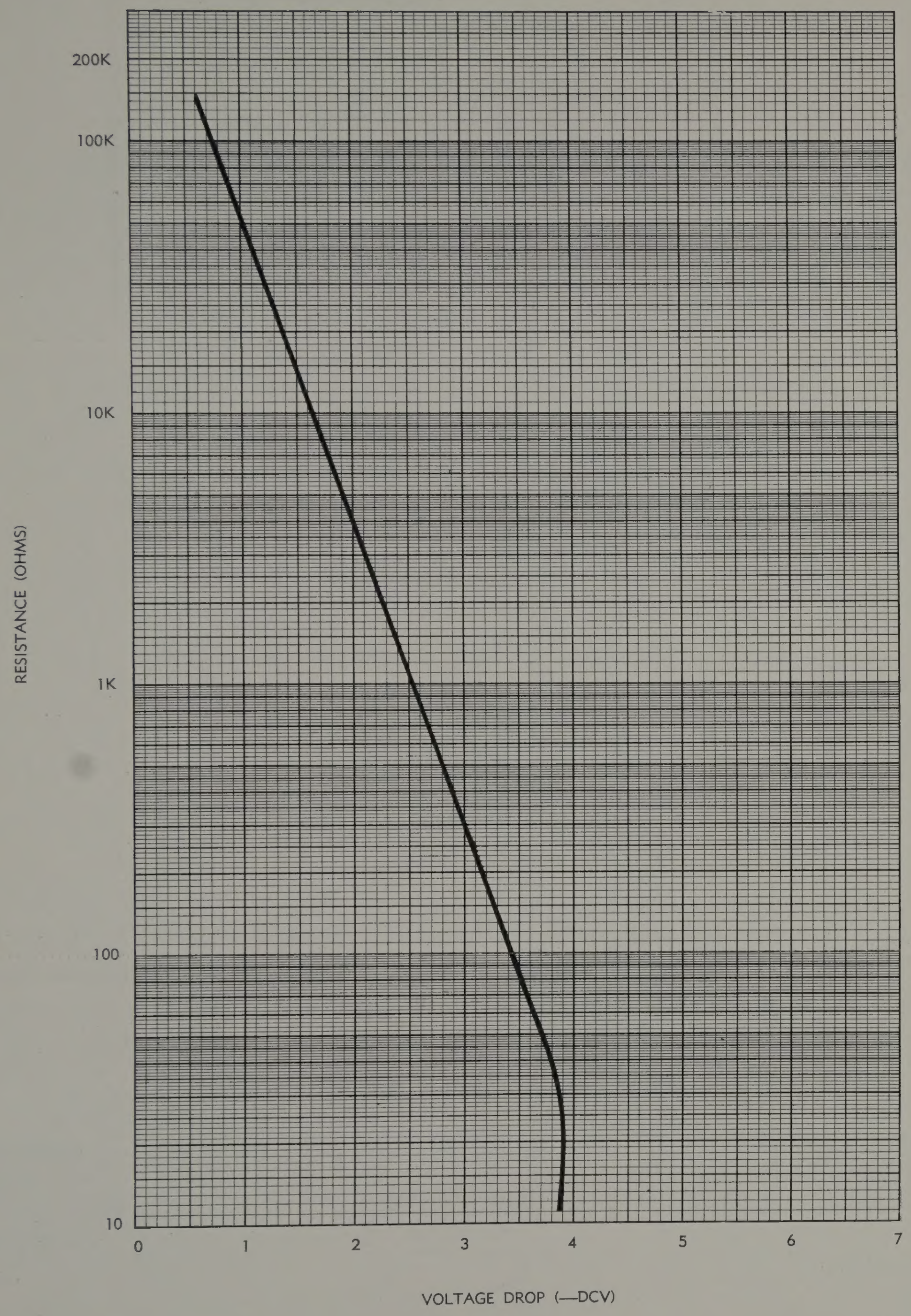


FIGURE 3. RESISTANCE CHARACTERISTIC OF ZENER DIODE

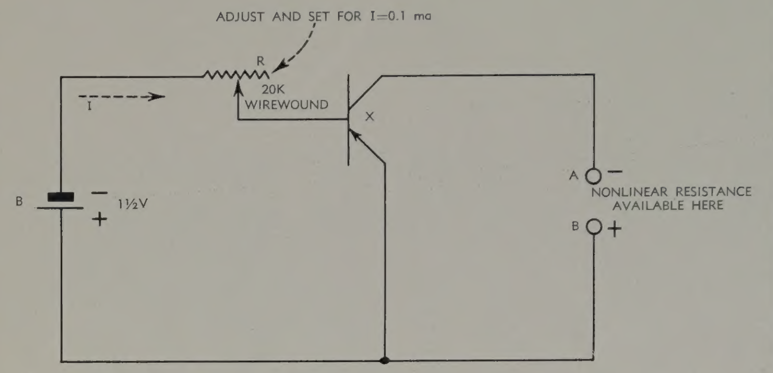


FIGURE 4. TRANSISTOR AS NONLINEAR RESISTOR

TRANSISTOR

The common-emitter-connected transistor will provide a nonlinear resistance in its collector-emitter (output) circuit when a small fixed bias current is supplied to its base-emitter (input) circuit. Figure 4 shows the circuit: X is the transistor, B a 1½-volt d-c bias source, and R a 20,000-ohm wirewound rheostat for setting the bias current to 0.1 milliampere. The internal collector-emitter resistance varies nonlinearly as a voltage applied to terminals A and B (with A negative) is varied linearly.

Conventional Small-Signal Transistor. For low-voltage applications (i. e., where the d-c voltage drop across the transistor will not exceed 22½ v), a conventional, small-signal transistor is satisfactory. Common-emitter response curves for various transistors may be inspected for the absolute resistance values and resistance variation desired. (Resistance may be calculated from the collector voltage and collector current values obtained from the curves: R=Vc/Ic.)

Figure 5 shows the collector resistance variation for the circuit given in Figure 4. When rheostat R is set for a bias current, I, of 0.1 ma, the resistance varies from 118 ohms at a collector-to-emitter voltage drop of 1 v to 1160 ohms at 12 volts. (This resistance change of 9.84:1 corresponds to a current change from 8.5 ma to 10.32 ma.) The transistor is RCA Type 2N109. Unlike the previous examples, here the resistance varies *directly* as the applied voltage; and although it is very nearly linear, it is voltage-dependent.

Power Transistor. When higher voltage and/or current must be used, a suitable power transistor must be chosen. The circuit is the same as Figure 4, except that B and R must be chosen for higher bias current. With a Delco Type 2N2827 transistor, biased at 1 ma, the resistance increases from 40 ohms to 156 ohms as the voltage is increased from 5 v to 25 v (corresponding to a current increase from 125 ma to 160 ma). When this transistor is biased at 4 ma, the resistance increases from 17.7 ohms at 5 v to 61.6 ohms at 20 v (corresponding to a current increase from 280 ma to 325 ma).

Field Effect Transistor. Operation of the unipolar field effect transistor (FET) approximates that of a vacuum tube more closely than is possible with a conventional transistor. In particular, the input impedance (resistance) of the FET is very high (similar to the tube grid input), so this device is essentially voltage operated as far as an input-bias signal is concerned.

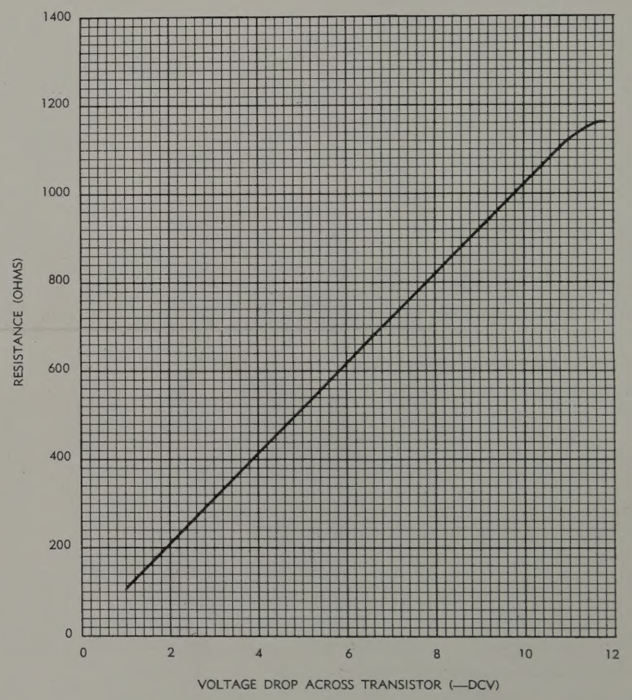
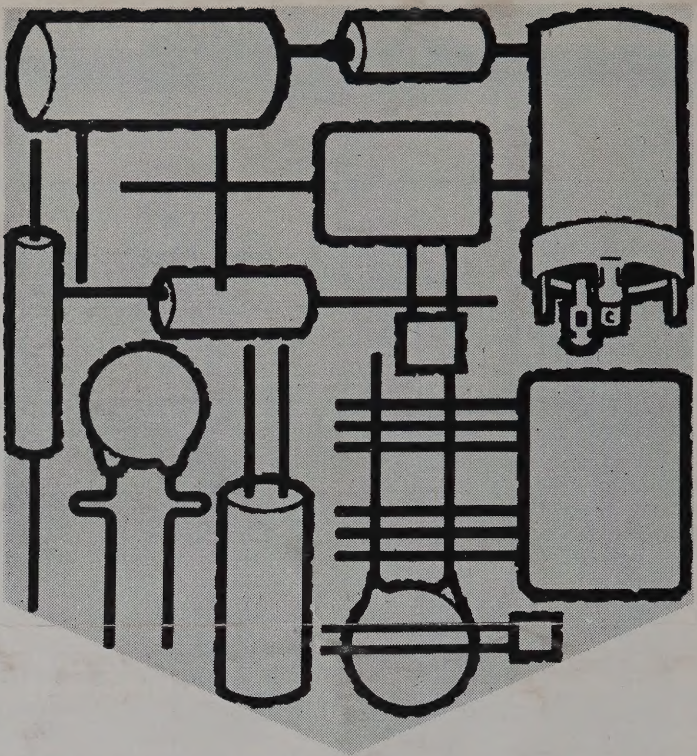


FIGURE 5. COLLECTOR RESISTANCE CHARACTERISTIC OF SMALL-SIGNAL TRANSISTOR



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